ACTIVE CONTROL OF LOW-SPEED FAN TONAL NOISE USING ACTUATORS MOUNTED IN STATOR VANES: PART III RESULTS

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Abstract

A test program to demonstrate simplification of Active Noise Control (ANC) systems relative to standard techniques was performed on the NASA Glenn Active Noise Control Fan from May through September 2001. The target mode was the m=2 circumferential mode generated by the rotor-stator interaction at 2BPF. Seven radials (combined inlet and exhaust) were present at this condition. Several different error-sensing strategies were implemented. Integration of the error-sensors with passive treatment was investigated. These were: (i) an in-duct linear axial array, (ii) an in-duct steering array, (iii) a pylon-mounted array, and (iv) a near-field boom array. The effect of incorporating passive treatment was investigated as well as reducing the actuator count. These simplified systems were compared to a fully ANC specified system. Modal data acquired using the Rotating Rake are presented for a range of corrected fan rpm. Simplified control has been demonstrated to be possible but requires a well-known and dominant mode signature. The documented results herein are part III of a three-part series of reports with the same base title. Part I and II document the control system and error-sensing design and implementation.

Introduction

A goal of the NASA Advanced Subsonic Technology Noise Reduction Program is the reduction in transport aircraft EPNL attributed to the engine by 6 dB relative to 1992 technology. A component of EPNL is fan tone noise caused by rotor-stator interaction and duct modal propagation.[1,2]

Theoretical and experimental work has shown that Active Noise Control (ANC) can significantly reduce the tone levels of ducted fans. NASA Glenn Research Center's (GRC) Active Noise Control Fan (ANCF) serves as a test bed to verify proposed ANC technologies. As the disturbance is tonal, active noise control has potential as a solution to fan/stator interaction noise. Prior experimental investigations of active noise control[3-5] have generally used fully specified systems.[6] The strictest requirement for fully specified systems is the number of sensors/actuators in an array to equal to twice the highest circumferential mode that can propagate. The number of arrays required is related to the highest radial mode in the m-order to be controlled. Thus controlling m=2 (with 7 radials) in a fan duct where up to m=+/-12 can propagate could require a maximum of 8 arrays each containing 25 components for a total of 200 microphones and 200 actuators. These systems have been shown to successfully reduce multiple radial modes, but concern has been expressed about the large number of components required. The systems implemented used fewer than the ideal maximum, but not substantially so.

An earlier effort reduce the number of components[7] was demonstrated on the ANCF. Reductions in selected farfield sectors were attempted using a wave-number sensing technique or farfield error-sensors and a single circumferential array source in a three radial environment. Reductions were modest, but the techniques were validated.

This report provides the acoustic results from the NAS1-99059 and 99060 contracts performed at the

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NASA Glenn Research Center Active Noise Control fan May through September 2001. This report should be considered Part III of a whole; Part I[8] and Part II[9] provide more detail of the analysis and development of the systems.

Experimental Apparatus

AAPL Facility

The Aero-Acoustic Propulsion Laboratory (AAPL) is an acoustically treated geodesic dome that houses the Powered Lift Rig (PLR), the Nozzle Acoustic Test Rig (NATR), and the Active Noise Control Fan (ANCF). The 130-ft.-diameter dome is 65-ft high and acts as a noise barrier, protecting adjacent Glenn buildings and surrounding residential communities from the high levels of noise produced by the rigs. For research, the dome serves provides an anechoic environment down to 125 Hz for acoustic measurement of aero-propulsion components.

ANCF Test Bed

A proof-of-concept test was performed on the NASA Glenn 48 in. Active Noise Control Fan[10,11] (ANCF) located in the AAPL. The ANCF is a ducted fan used to test noise reduction concepts (fig. 1). The 4-ft.-diameter fan produces a tip speed of ~425 ft/sec resulting in a Blade Passing Frequency (BPF) of approximately 500 Hz. A 16-bladed rotor in combination with a variable stator vane-count and axial-spacing produces the desired rotor-stator interaction modal content. No internal support struts are required since the center body and duct walls are fixed to the support structure (Internal struts could result in additional interaction acoustic duct modes, resulting in a more complicated mode structure.) Inflow and turbulence distortions that would introduce asymmetric loading of the blades are minimized by an inflow control device (ICD) at the inlet.

A set of 30-stator vanes spaced 1 chord (rotor chord = stator chord ~ 4.5 in.) from the rotor trailing edge, at the hub, was used for this test. The corrected fan speed range was from 1800 to 2300 crpm, in 100 crpm increments. The target test circumferential mode at 2BPF was m=2. Three radials were cut-on in the inlet below 2186 crpm; above 2186 crpm there were four radials. Two radials were present in the exhaust below 2143 crpm; above 2143 crpm there were three radials. The design test condition of seven cut-on radials occurred at 2200 and 2300 crpm. The corresponding 2BPF was 960 to 1227 Hz.

In-Duct Measurements

Acoustic mode in-duct levels were measured using the NASA rotating rake modal measurement system that independently measured the effect of the ANC system on each propagating mode. Time domain averaging is used to reduce noise

unsynchronized to fan rotation and narrow band spectra are used to extract the magnitude and phase of each m-order component for each microphone. Different m-orders appear as distinct spectral lines frequency shifted due to Doppler effects. A set of Bessel functions appropriate to the m-order is then fitted to the data in a least square sense to obtain the radial mode content. There are two rake microphone arrays for the ANCF, a seven-microphone array for the inlet and a six-microphone array for the exhaust (only one rake is installed at a time). A gear mechanism rotates the rakes at one-hundredth the rate of the fan. The microphone signals are sampled synchronously with the rotation of the fan and hence synchronously with the interaction spinning acoustic modes generated by the fan.

The result of the rake processing is a set of spinning mode amplitudes and phases at the rake location. It is assumed that reflections from duct terminations are negligible and that the spinning mode amplitudes represent the amplitudes of modes propagating from fan to the duct termination, and then radiating to the far field.

ANC System

The program objective was to simplify the control strategy. For this program, simplification was defined as reduction of the number of components used by the ANC system compared to previous ANC concepts. All variations in sensing arrays used the full set of actuators. A separate configuration investigated the effect of reducing the number of actuators used. The effect of incorporating passive treatment in the ANC system was also tested. Parts I and II fully detail the ANC systems.

The ANC system consisted of 30 ANCF stator vanes modified to allow seven actuators to be installed in each vane. These actuators were driven with 105 current controlled amplifiers, two actuators per amplifier. The actuators were driven in seven independent 30 element circumferential arrays. Fourteen 10-element circumferential arrays of microphones in the ANCF were used for the error inputs. Subsets were chosen to implement the simplification strategies from these global sets. Figure 2 shows a schematic of the control system hardware mounted on the ANCF.

Test Results

The primary data reported herein (Part I) is modal breakdown as measured by the rotating rake. The results are limited to target mode PWL reductions obtained because the spillover generated by the actuators contaminated the over-all PWL measurements. The unique measurement ability of the rotating rake allowed the effects of the ANC on the target acoustic mode to separated from the

contamination. Farfield SPL directivity results are also presented for configurations that target limited control to sectors in the farfield.

Circumferential Error Sensing Arrays

Control of spinning modes using in-duct circumferential arrays was selected as the baseline control case. The standard technique of choosing the number of microphones in each array based on the maximum m-order to be detected was used. At the highest frequency of interest circumferential modes between m=-12 and 12 could propagate in the ANCF. Ordinarily, since m=2 is the target mode, 15 microphones in each array would be required to prevent aliasing into other propagating circumferential modes. However, experience with the ANCF has shown that for this operating condition ten microphones per array are adequate to prevent any significant problems with aliasing. The number of circumferential arrays was determined based on the highest radial cut-on at the target circumferential mode. This requirement dictated four circumferential arrays in the inlet, and three in the exhaust. Thus, 70 error-sensing microphones were required to control the seven radials.

The hard-wall configuration (treatment was taped over) with a fan speed of 2200 crpm was selected to investigate the optimum sensor configuration for the inlet. Various selections of four arrays of the eight available were chosen to control the four radial modes in the inlet. Figure 3a shows the reduction achieved using selected inlet arrays. Refer back to figure 2 to determine the axial location of the arrays. For a given configuration, a variation of several dB in noise reduction was observed for a given configuration due to a variety of causes, such as how recently the plant transfer functions had been measured, changes in various filter and gain settings, etc. The performance was not strongly dependent on the error sensor configuration, a result consistent with the simulation results in reference 8. However, configuration 1 [LIP1, DUCT1, SW1, SW2] which provided about 16 dB of reduction in the target mode, and configuration 3 [LIP1, LIP2, DUCT1, DUCT2] which provided about 13 dB reduction appeared to provide the best performance and were chosen as the optimum to be used for further control algorithm configurations testing. Other configurations provided nominally 10 dB of reduction. The axial extent of these configurations is 38.6 and 18.6 in., respectively.

These configurations were tested over the range of 1800 to 2300 crpm and the results are compared on figure 3b. The noise reduction ranges from a low of 6 dB at 2000 RPM to a high of 18 dB at 2200 crpm. At 2200 crpm, several control attempts were made for each configuration and the range of results is shown to overlap suggesting nearly identical results over the entire crpm range.

The effect on m=2 in the exhaust when controlling the inlet is shown in figure 3c. A significant result is that modest to significant reduction (1 to 13 dB) is achieved in the exhaust when controlling only the inlet. Previous ANC experiments have often showed an increase in the exhaust when controlling the inlet. Neither was this result predicted by the simulations described in Part I. In fact, those simulations predicted a slight increase in exhaust duct radiation at 2200 RPM. This result is significant because it indicates that the control system can focus on just the inlet if most of the sound radiation comes from there and not fear that sound radiation from the exhaust will increase but might in fact decrease. The beneficial result seen here may be due to the close coupling of the actuators to the stator source.

The results of the exhaust array selection are shown in figure 4a. The data shown are the reductions obtained in the exhaust, at 2200 crpm fan speed, with three or more of the six error sensor arrays in the exhaust selected. As indicated by the simulations, there is not a large difference in performance for different sensor arrays. The three inner arrays, or all six arrays (which is over specified), provide somewhat better performance. Figure 4b shows these cases for the tested fan speed range. Up to ten dB reduction occurs, with using three resulting in the best reduction. Figure 4c shows the inlet levels obtained when controlling in the exhaust. Again, the very interesting result is that up to 7 dB of reduction is obtained in the inlet when the exhaust is controlled. This is particularly significant because the uncontrolled fan inlet levels are 6 to 15 dB higher than the exhaust.

Simultaneous inlet and exhaust (dual) control was also demonstrated. Figure 5a shows the inlet levels obtained with dual control; figure 5b that obtained for the exhaust. It is significant that the reduction obtained with dual control is less than that with uni-directional control, regardless of which duct is being controlled. That is, controlling solely in the inlet (which is under-specified) results in better reductions in the inlet and exhaust than that obtained by dual control (which is fully specified). The reduction obtained with dual control appears to be limited by the exhaust. The reason for this unexpected result is that the amplitudes demanded of the actuators by the controller exceed their capability. This was obvious during the testing because the voltages applied to the actuators could be seem in oscilloscope traces to be clipping, i.e., the sine waves were flat topped. The actuator displacement was limited by the maximum voltage that could be generated by the power amplifiers. This occurred rarely when controlling with only inlet error sensors or only exhaust error sensors. The analytical results in Part I correctly predicted that simultaneous control

would require nearly double the actuator amplitude of control in either the inlet or exhaust alone. What the predictions did not indicate was that the actuator amplitudes demanded would be greater than their capabilities, possibly due to inaccuracies in the modeling. While errors of a few dB may be acceptable for noise predictions, they may not be for determining actuator displacement requirements. For example, a 3 dB discrepancy could lead to over a 40 percent error in actuator amplitude predictions. It may also be that the convergence based on the transfer functions from the initial system identification is more susceptible to error as the size of the matrix increases (number of control channels).

Passive Treatment

Studies have shown that reducing passive treatment to install an active noise control system will result in penalties due to the loss of treatment that may be greater than that obtained from the ANC. A passively treated duct section was installed in the inlet to investigate incorporating passive treatment into an ANC system. Comparisons were made of the ANC performance with baseline hard-wall (treated section taped over) to ANC performance with the treated section exposed. A comparison was made between the typical method of using the error sensing microphones upstream of the exposed treatment and embedding the microphones in the treatment. Embedding the error microphones in the treatment can simplify the system by shortening the inlet length.

A duct section with bulk passive treatment of 1.4-0.5i design specific impedance and an L/D of 0.375 was installed in the inlet. The two inlet control error arrays were used: a standard set with all four circumferential error sensing arrays upstream of the treatment; the other with two of the four arrays embedded in the treatment. These are the same optimum arrays previously selected.

Figure 6 shows the reduction obtained in the target mode PWL with the liner section exposed. Note that the treatment alone resulted in about 4 dB of reduction in m=2 over the entire fan speed range. The results are generally identical to the full hardwall case. The reduced levels achieved with embedded case are similar to those obtained with the hardwall demonstrating that control can successfully achieved with standard LMS convergence algorithms in such a case. The demonstrated result that the embedded sensors are similar to or better than those obtained with the sensors in the upstream untreated duct section is an important, since it indicates that here is no noise reduction performance penalty associated with embedding error sensors in wall treatments. The ability to embed the sensors in the treatment increases the flexibility in the locating error sensors

in ANC systems and avoids any noise reduction performance penalties associated with eliminating a portion of the passive treatment.

Reduced Actuator Count

Current control strategies dictate that seven independent actuators to control the seven radials are required. For 7-actuators per vane and 30 vanes, the total actuator count was 210. Selected subsets of actuators were tested to demonstrate the feasibility of lowering the actuator count.

A possible method to reduce system complexity is to use fewer actuator sets than normally indicated by control theory. The four control sensor arrays of configuration 3 were used. The control system was thus 4×4. The two different actuator array configurations were: all four arrays on the stator leading edge and a distributed set with two arrays on the leading edge and two on the trailing edge. Figure 7 shows the actuators mounted in the vane.

Figure 8a shows the reduction obtained in the target mode PWL in the inlet when using two-sets of four-array actuators. The leading edge actuator array configuration shows a significant decrease in performance compared to using all seven actuator arrays. The simulations (Part I) at 2200 RPM on the other hand indicated similar actuator displacements with either actuator configuration suggesting that the noise reduction performance would also be similar. The configuration with actuator arrays on both the leading and trailing edges performed better than the leading edge configuration, but nowhere near as well as the full set with up to 10 dB of reduction only at selected fan speeds. For this configuration, the simulations indicated about 50 percent higher actuator displacements than the seven-actuator configuration, which would be expected to lead to some performance degradation if the actuators approached their limiting displacements.

Figure 8b shows exhaust reduction obtained controlling in the exhaust using only a three-actuator arrays consisting of one array on the leading edge and two on the trailing edge and the three microphone arrays on the inner wall. Useful reduction of up to 12 dB occurs and here the results are nearly as good as the full set except at 2200 crpm. Simulations indicated that the actuator displacements would nearly double for this configuration compared to the seven-actuator array arrangement. Such large displacement requirements indicate that performance degradation is likely.

In-Duct Linear Error Sensing Array

Instead of using circumferential arrays to detect m=2, a single microphone per array, distributed axially, of the microphone arrays was used. The minimum number of microphones required is still

equal to the number of radials present; four in the inlet and three in exhaust for a total of seven. In the inlet a single microphone from ICD1, ICD2, DUCT1 and DUCT2 was chosen to form a four element axial line array, and; in the exhaust a single microphone from each of the three arrays on the inner wall were selected based on the error-array optimization results. In both cases, all seven actuator arrays were activated. This concept requires the target circumferential mode to be dominant.

Figure 9 shows the in-duct PWL and reductions in the PWL for the target mode for the linear control array as measured by the rotating rake. The linear array control results are contaminated due to the high extraneous circumferential modes. Without the ability to filter out wall pressure due to non-m=2 modes, the control algorithm 'uses' those pressures to falsely cause the P_{rms} levels measured by microphones to be reduced. The results show that the reduction obtained is very modest, even slight increases as a result. It is important to recognize that the spillover of the actuators did not provide a fair test for the linear error array though the modest reductions indicated the concept might be valid.

In-Duct Steering Array

A steering filter modeling the transfer function between the error sensors and radial was used to attempt control of individual radials. The derivation of the steering array is detailed in Part I. In summary, a linear subset, axially distributed, of error microphones was chosen. A matrix weights the microphones such that only an individual radial is sensed and therefore controlled. The steering array was implemented in the inlet using three available microphones with four actuator sets and four microphones (3×4 control) with seven actuator sets (4×7 control). The weighting matrix was implemented to control each of the three radials propagating at 1900 crpm.

The results are shown in figure 10. Though control was achieved for all but one of the weightings, the target radial mode was not generally one most reduced. This is not at all surprising considering the analytical results discussed in Part I showed that the small number of arrays and the large spacing between then seriously inhibited the ability of the arrays to emphasize a single radial mode and de-emphasize the others.

Boom Error Sensing Array

A boom was located outside the fan duct in the horizontal plane, approximately 10 feet from the centerline as shown in figure 11. The goal was to demonstrate the feasibility of reducing selected sectors of the farfield directivity that have the greatest impact on noise. This would be a more realistic application of the farfield error microphone technique. The boom array error sensing input weighting used two methods: a radial based filtering to attempt to control individual radials and an angle based method to control sectors in the farfield.

The radial control weighting results at 2300 crpm are shown in figure 12. The best results were with the m=2 weighted control attempt: 3.5 dB with the (2,0) reduced 10 dB. The n=2 weighted control was nearly as successful. Control weighting of other individual radials attempts was not successful in the overall m=2 reductions and for individual radials. Like the steering array, the targeted mode was not necessarily the one reduced the most; which may indicate the propagation from the duct was not properly determined possibly due to contamination.

The in-duct results from weighting the boom microphones to control local sectors in the farfield are shown in figure 13. Control of two sectors 45° and 30° were attempted over a fan speed range of 2000 to 2300 crpm. At 2300 crpm the 30° control reduced the (2,0) mode dramatically (~22 dB) and the higher radials modestly. The 45° control was more distributed over the radials, resulting in better control in the total mode. As the crpm is reduced, the 30° control becomes less effective, while the 45° control stays equally effective over the crpm range. This is due to the primary lobe radiating at a higher farfield angle as the cut-off ratio (i.e., rpm) is reduced.

Pylon Error Sensing Array

Turbofan engines typically have a pylon or bifurcation in the exhaust duct. The ANCF exhaust duct was modified by installing two radial surfaces 180° apart, in the vertical plane to simulate a bifurcation, as illustrated in figure 14. This surface can provide additional locations to mount error-sensing microphones. In addition, the radial extent of the pylon/bifurcation may provide radial information to the control system. Twenty microphones were distributed radially (five on each surface).

The pylon control array was unsuccessful above the cut-on of the three radial in the exhaust. Several subsets of the pylon microphones, some configured with circumferential arrays, as shown on the table in figure 15 were used for error inputs. The controller converged to a reduction, but the radial array was apparently unable to distinguish between the radials at different m-orders due to the profile similarity. At 1800 crpm the pylon array achieved up to 10 db reduction in m=2 PWL. The best configuration used an inner and outer circumferential array with four pylon microphones (two each from two pylon sides). This is considered the baseline since the two circumferential arrays alone meet the criteria to control two radials. The configuration using six microphones (three on two pylon faces) performed

very well and met the goal of using only radially distributed microphones. It may be that more microphones are required in the radial distribution than the number of radials present.

Test Conclusions

Several different control strategies for reducing the complexity of an Active Noise Control system were tested and compared to the conventional method of using circumferential modal decomposition with the number of inputs and outputs at least equal to the number of radials to be controlled. The baseline configuration required 210 actuators and 70 microphones with 7 independent control channels. The incorporation of error sensing components into passive treatment was evaluated.

The baseline control strategy was successful, resulting in control of the seven radials in m=2 (four in the inlet, three in the exhaust) of up to 18.5 dB in the inlet; 13.5 dB in the exhaust. An important result from the baseline configuration was the simultaneous reduction in the inlet and exhaust when control was attempted in the inlet only. This under-specified control (4 inputs $\times$ 7 outputs) is a substantial simplification. The reason for this dual control maybe due to the close physical proximity of the anti-source (actuators) and the source (stator vanes). Other configurations in this test tended to confirm this result. It is important to determine if this result can be generalized.

Embedding of the error sensing microphones into the treatment resulted in similar or better reduction than the standard method of using only error sensing arrays upstream of the treatment. Combining the duct length required for error arrays with treatment avoids the problem of increasing the duct length or eliminating treatment.

The reduced actuator set to four in the inlet or three in the exhaust resulted in about 12 dB reduction in each direction at fixed crpm with modest reductions at other speeds.

Methods to reduce the complexity of the input arrays included an in duct steering array, linear array, a radial array located on the pylon, and a near field (outside the duct) boom array. The steering array reduced individual radials, but not necessarily the target radial. Better discrimination and determination of the radial weighting function may be required. The linear array was modestly successful (up to 9 dB) at a few speeds. The boom array reduced the lower radials substantially, which might contribute most fly-over noise as it was designed. Since these methods generally require an acoustic environment dominated by the target mode, they were handicapped by the extreme spillover generated by the actuators. The reason for the poor modal content

of the actuators is not known, but suspected to be due to structural resonance and/or coupling.

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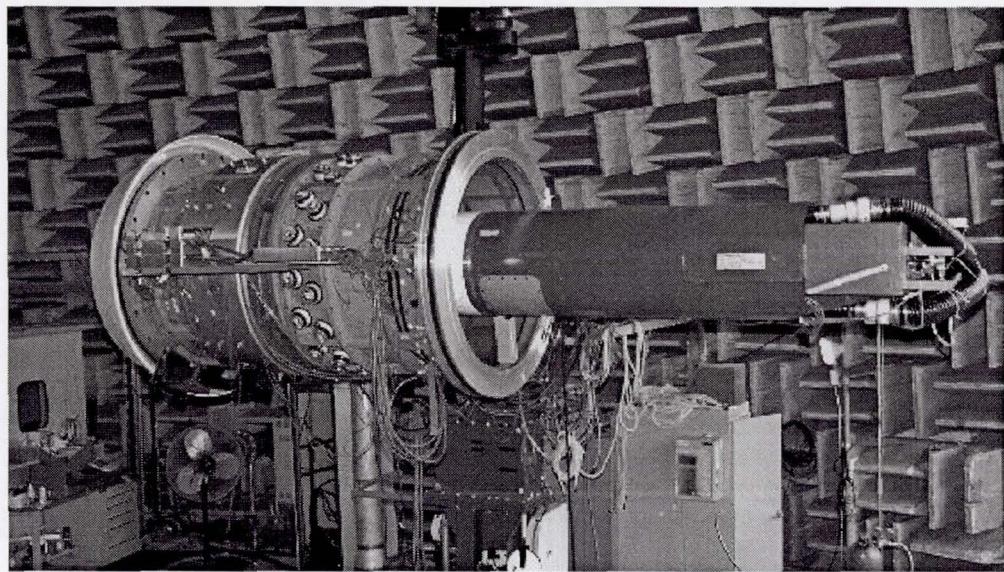
FIGURE 1. PHOTOGRAPH OF ACTIVE NOISE CONTROL SYSTEM HARDWARE

Nomenclature and distance from stator leading edge of circular arrays

INLET		EXHAUST	
lip1	61.9"	innerA	22.6"
lip2	56.9"	innerB	30.1"
duct1	46.8"	innerC	33.9"
duct2	41.3"		
duct3	37.6"	outerD	23.5"
softwall1	29.8"	outerE	30.9"
softwall2	25.6"	outerF	34.7"
softwall3	19.1"		
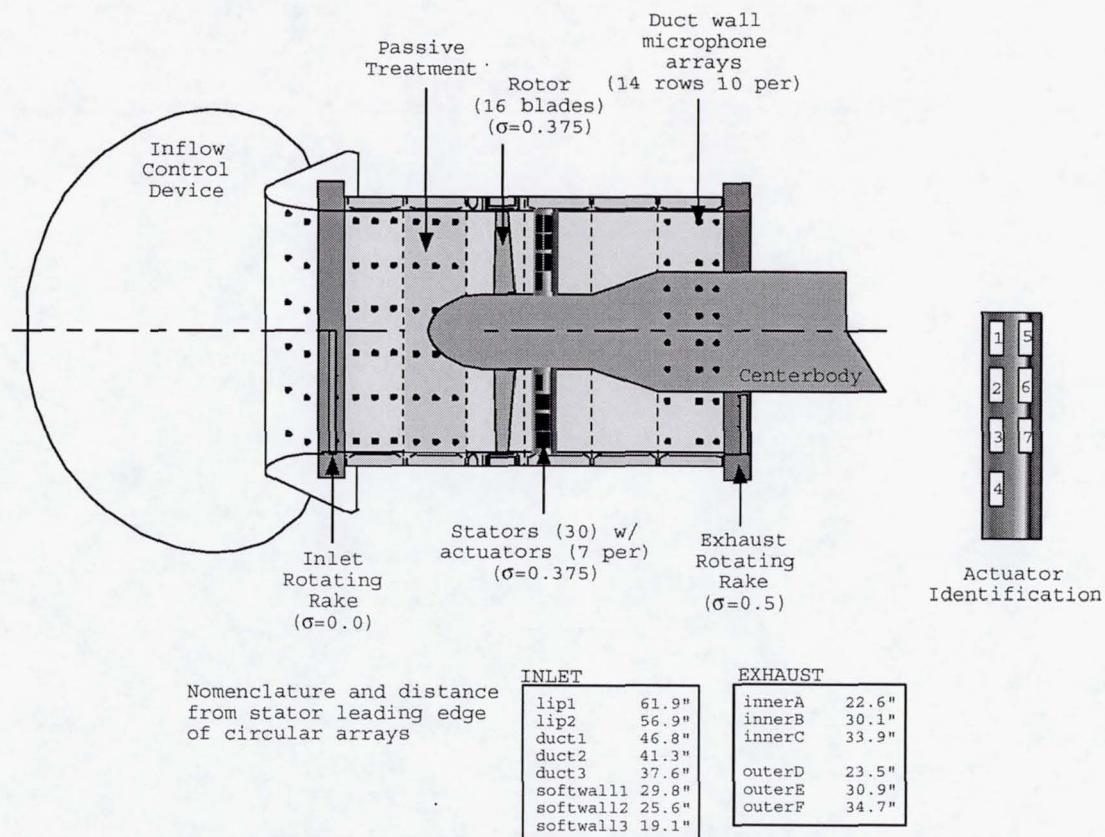
FIGURE 2. SCHEMATIC OF ACTIVE NOISE CONTROL SYSTEM HARDWARE

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m=2 radial mode decomposition
2BPF * Ω = 2200

ANC error sensing
array configurations
(refer to fig 2)

■ CONTROL OFF

▨ [LIP1,DUCT1,SW1,SW3]

□ [LIP2,DUCT2,SW1,SW3]

■ [LIP1,LIP2,DUCT1,DUCT3]

▨ [LIP1,LIP2,DUCT1,DUCT2,DUCT3]

▨ [LIP1,LIP2,DUCT1,DUCT2]

a) Error Sensor Optimization

target mode   ANC error sensing   ■ CONTROL OFF
m=2 PWL only   array configurations
                     (refer to fig 2)   ▲ [LIP1,DUCT1,SW1,SW3]

                                               ● [LIP1,LIP2,DUCT1,DUCT2]

b) Measured in Inlet

c) Measured in Exhaust

FIGURE 3 RESULTS FROM APPLYING CONTROL IN INLET DUCT

m=2 radial mode decomposition
2BPF * Ω = 2200

ANC error sensing
array configurations
(refer to fig 2)

CONTROL OFF
3 OUTER WALL
3 INNER WALL
Ainner, Eouter, Cinner
ALL 6

a) Error Sensor Optimization

target mode
m=2 PWL only

ANC error sensing
array configurations
(refer to fig 2)

CONTROL OFF

▲ 3 INNER WALL

● 3 OUTER WALL

b) Measured in Inlet

c) Measured in Exhaust

FIGURE 4 RESULTS FROM APPLYING CONTROL IN EXHAUST DUCT

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target mode
m=2 PWL only

ANC error sensing
array configurations
(refer to fig 2)

[LIP1,DUCT1,SW1,SW3] (inlet)

■ CONTROL OFF

▲ +3 INNER WALL
(exhaust)

● 3 OUTER WALL
(exhaust)

a) Measured in Inlet

b) Measured in Exhaust

FIGURE 5. RESULTS FROM APPLYING DUAL CONTROL
(SIMULTANEOUS CONTROL IN INLET AND EXHAUST)

m=2 target
mode PWL only

ANC error sensing
array configurations
(refer to fig 2)

■ HW CONTROL OFF

□ SW CONTROL OFF

▲ [LIP1,DUCT1,SW1,SW3]

● [LIP1,LIP2,DUCT1,DUCT2]
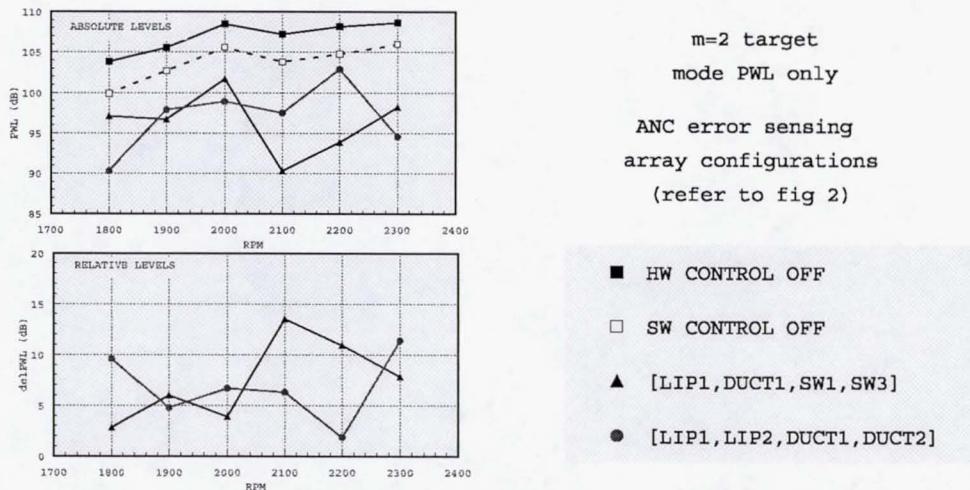
FIGURE 6. SOFTWALL INTEGRATION CONTROL RESULTS IN INLET

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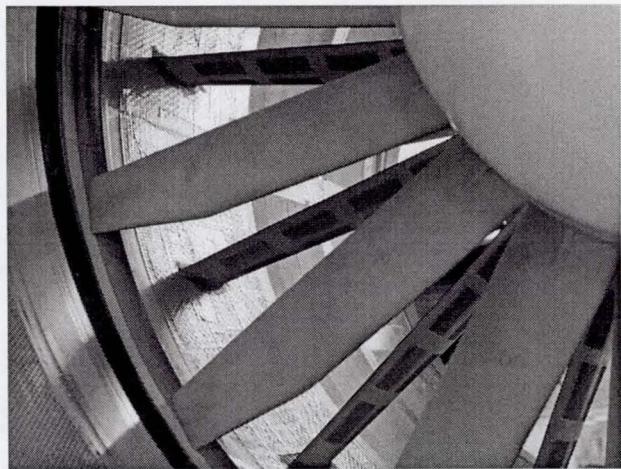
a) Suction Side
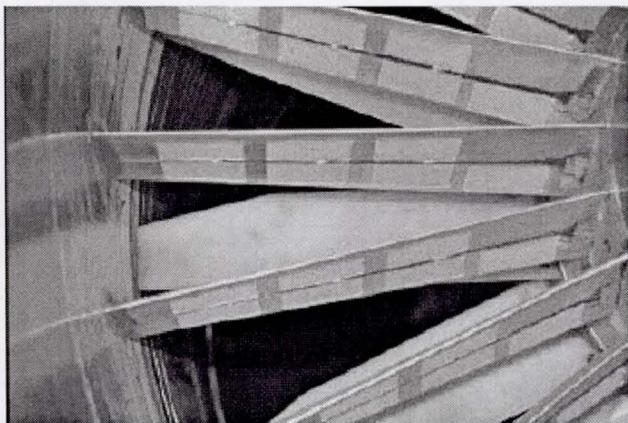
b) Pressure Side
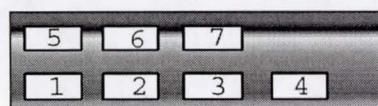
c) Actuator Identification

FIGURE 7. ACTUATORS MOUNTED IN STATOR VANES

a) Measured in Inlet

b) Measured in Exhaust
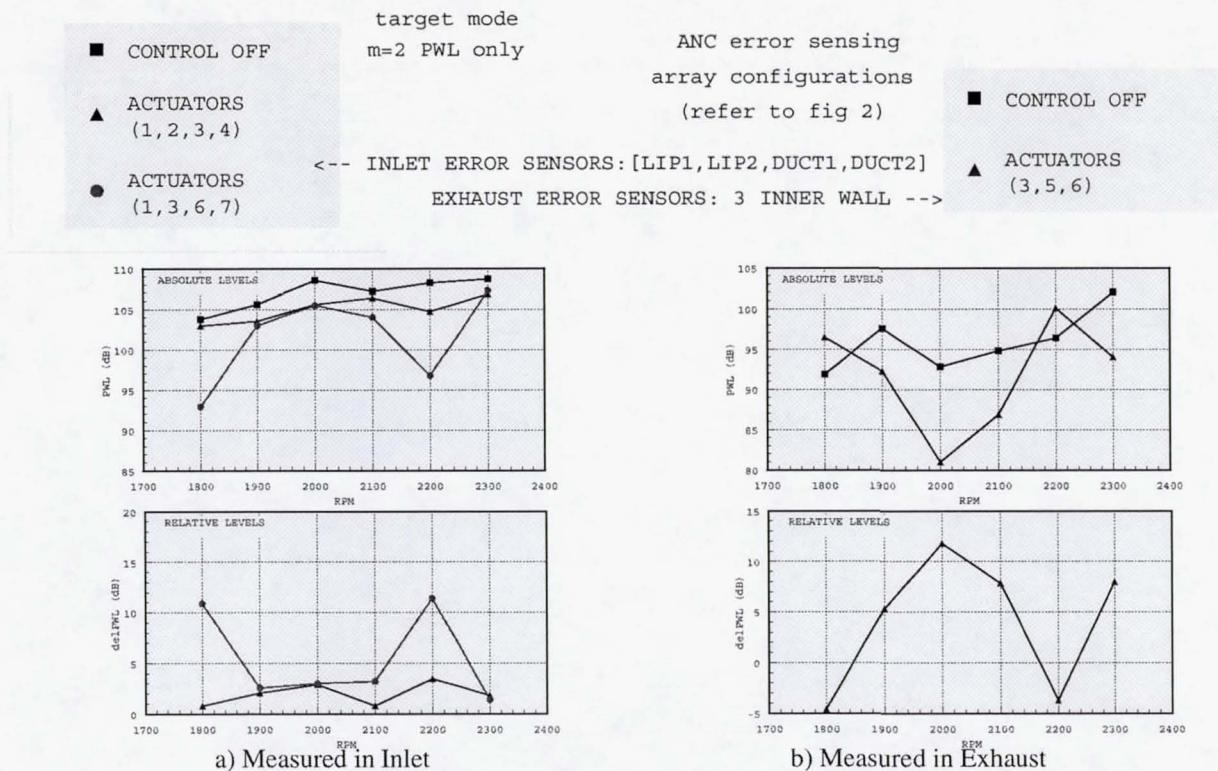
FIGURE 8. REDUCED ACTUATOR SET CONTROL RESULTS

target mode
m=2 PWL only

ANC error sensing
array configurations
(refer to fig 2)

INLET ERROR SENSORS:
[LIP1,LIP2,DUCT1,DUCT2]

■ HW CONTROL OFF

▲ HW LINEAR ARRAY

□ SW CONTROL OFF
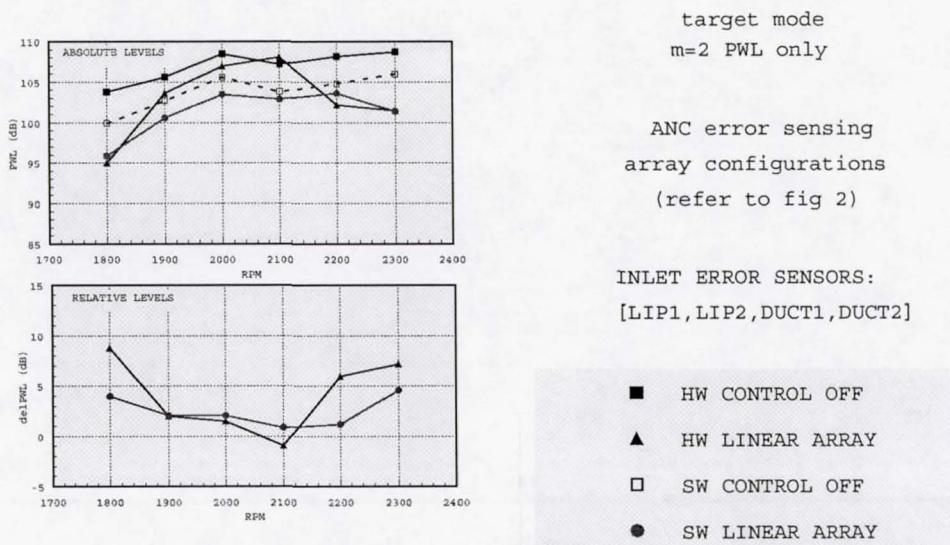
● SW LINEAR ARRAY

FIGURE 9. LINEAR ARRAY CONTROL RESULTS IN INLET

target mode
m=2 PWL only

2BPF * Ω = 2200

TYPE of
RADIAL CONTROL
ATTEMPTED

■ Off

■ n=0 (3x4)

□ n=1 (3x4)

□ n=2 (3x4)

■ n=0 (4x7)

■ n=1 (4x7)

□ n=2 (4x7)
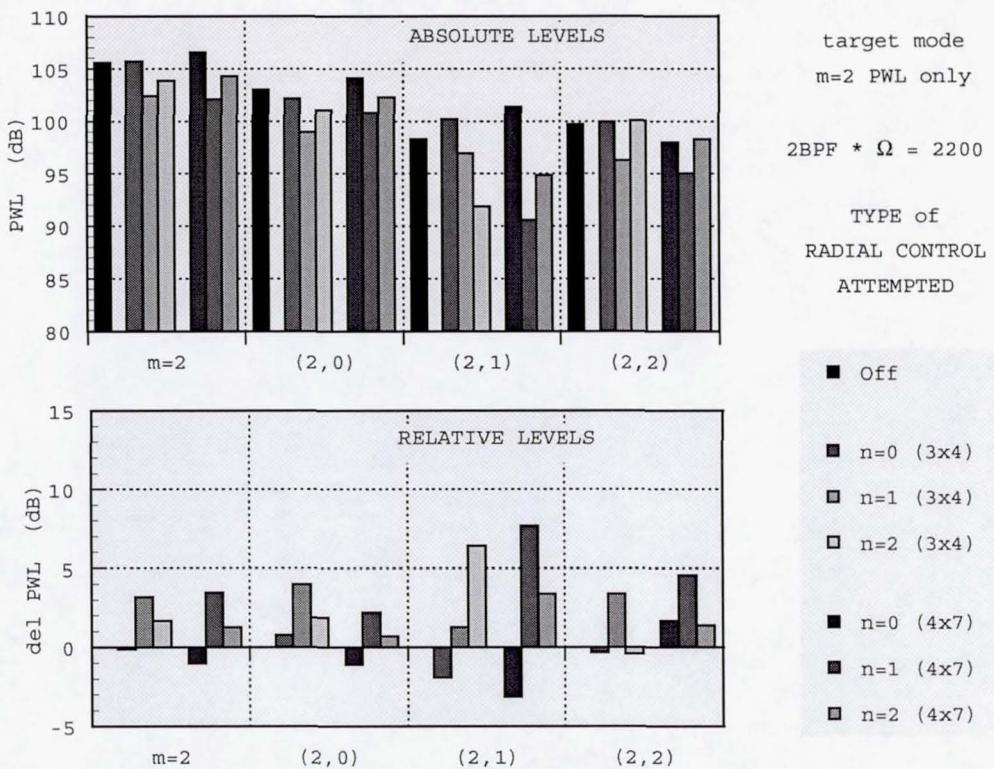
FIGURE 10. STEERING ARRAY CONTROL RESULTS IN INLET

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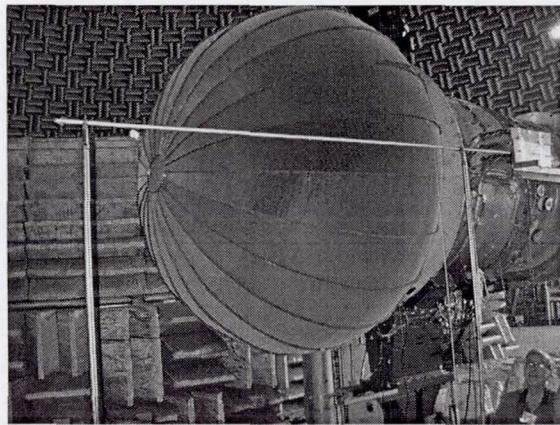
FIGURE 11. LINEAR INLET MICROPHONE BOOM ALONGSIDE ANCF ICD
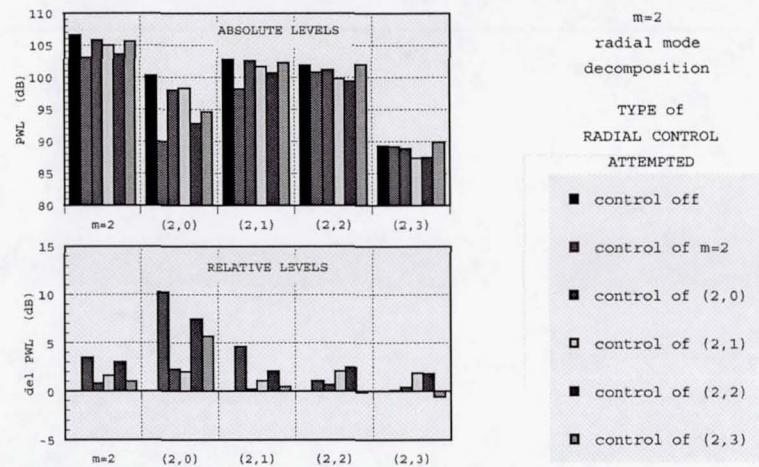
FIGURE 12. BOOM ARRAY RADIAL CONTROL INLET RESULTS
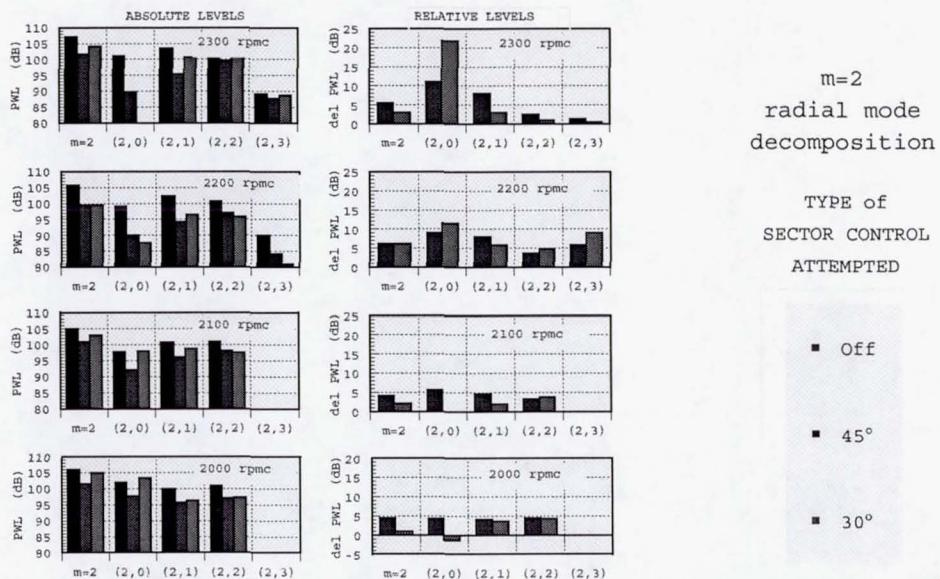
FIGURE 13. BOOM ARRAY ANGLE CONTROL INLET RESULTS

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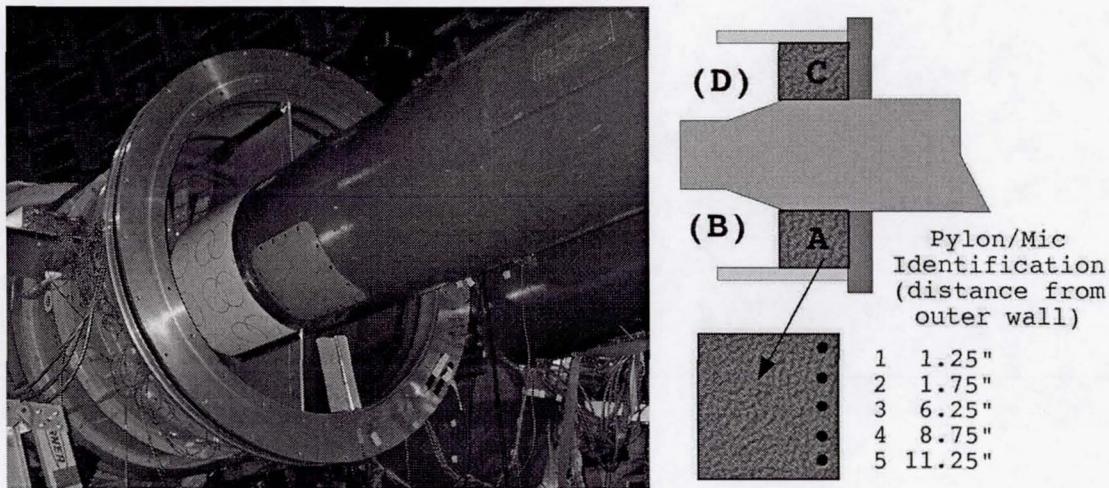
FIGURE 14. PLYWOOD PYLONS WITH RADIALLY
SPACED MICROPHONES IN ANCF EXHAUST DUCT
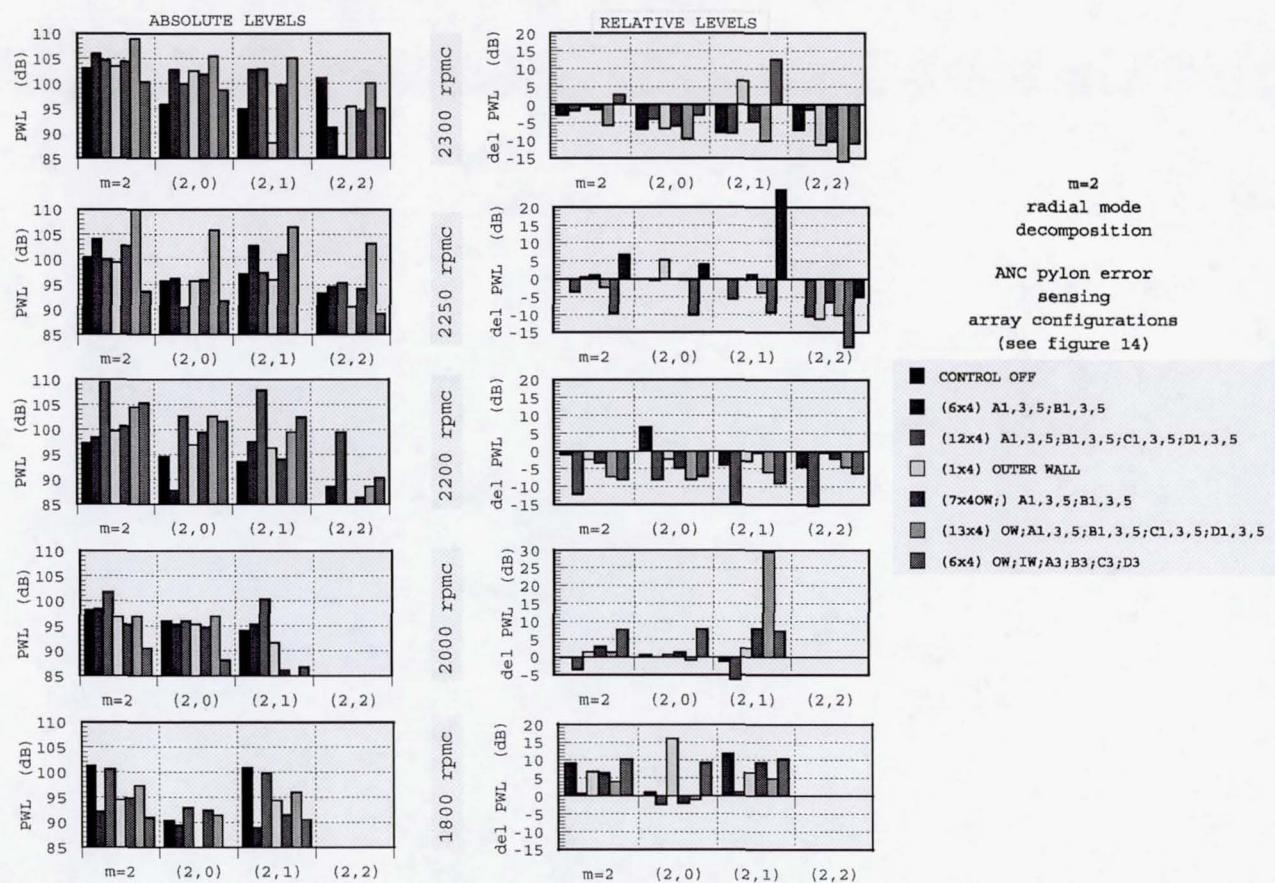
FIGURE 15. PYLON ARRAY CONTROL EXHAUST RESULTS